Single particle strength restoration and nuclear transparency in high Q^2 exclusive $(e, e'p)$ reactions

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ABSTRACT

Quasifree $(e, e'p)$ reactions at $Q^2 \sim 0.1 GeV^2$ observed a strong quenching of the single-particle valence strength. This precluded unambiguous measurement of nuclear transparency in quasifree (e,e'p) reactions at $Q^2 \geq 1\, GeV^2$. We argue that the high-energy nuclear transparency in the transverse kinematics weakly depends on the probability of the short-range correlations and can be accurately determined using information on the cross section of the (e, e') reaction at $x \sim 1$ and $Q^2 \sim 1 \div 2 GeV^2$. We find that the Glauber approximation well describes E91-013 and NE18 (e,e'p) data at $2 \leq Q^2 \leq 4 GeV^2$ without any significant quenching. This gives further support to our observation that the quenching of nuclear levels strongly depends on the resolution (Q^2) and practically disappears at $Q^2 \geq 1\, GeV^2$.

1 Introduction

Quasi-free knockout (e,e'p) reactions were used for a long time to study nuclear structure at the energy transfer $q_0 \leq 500 MeV$, for a review see [1, 2, 3]. One of the important findings of these studies was an observation of suppression of the single-particle valence strength as compared to the calculations using the nuclear shell model wave functions. This phenomenon of quenching in the low energy physics is naturally explained in the nuclear quasiparticle theory[4] as a result of the single particle strength fragmentation over wide excitation energy range due to the long and short range nucleon-nucleon correlations(for the recent review see e.g. [5]). Recently a thorough comparison of all recent low energy data for $^{12}C(e, e'p)$ was

performed in [6]. It is found that the data from different experiments are consistent with each other and require a very substantial reduction of the s- and p- shell strength in $^{12}C(e, e'p)$ at $Q^2 \leq 0.3\,GeV^2$ by the factor

$$\eta(^{12}C) = .57 \pm .02. \tag{1}$$

If the quenching did not depend on Q^2, this finding would strongly affect the interpretation of the recent (e,e'p) experiments at high energies and momentum transfers [7, 8]. These experiments were performed to study the nuclear transparency $\mathbf{T}$ as a function of the momentum transfer at $1\,GeV^2 \leq Q^2 \leq 7\,GeV^2$ on several nuclei with the main goal to search for the color transparency effects [9, 10, 11]. According to the theoretical predictions[12, 13] the color transparency could be expected at these momentum transfers as a 10% increase of the nuclear transparency with increase of Q^2. Hence, a high precision determination of all the nuclear characteristics influencing evaluation of $\mathbf{T}$ is very important.

Experimentally, the nuclear transparency $\mathbf{T}$ is defined as the ratio of the observed cross section to the cross section calculated in the plane-wave impulse approximation(PWIA). The delicate point here is to estimate precisely how large the latter is for the kinematics of the particular experiment. The PWIA cross section is

$$\sigma_{pwia} = F_{kin}\sigma_{cc1}^{ep} \int\ S(\mathbf{k}, E)\, d^3k\, d\, E, \tag{2}$$

where F_{kin} is the kinematic factor and σ_{cc1}^{ep} [14] is the off-shell extrapolation of the elastic ep cross section. If the momenta of bound nucleons, $\mathbf{k}$, and excitation energies of the residual nuclei, E, in (e,e'p) are not too large, there are practically no differences between different models for off-shell extrapolation of σ^{ep}. Hence, the main problem is to determine accurately enough the integral over the nuclear spectral function $S(\mathbf{k}, E)$. In high Q^2 (e,e'p) experiments [7, 8] the $S(\mathbf{k}, E)$ was calculated in the independent particle shell model. To correct this calculation for the missing single particle strength in the kinematics of the experiment an additional correction factor $f(A)$ was introduced, leading to

$$\int S(\mathbf{k}, E)\, d\, E\, d^3\, k = f(A) \cdot \int S_{IPSM}(\mathbf{k}, E)d\, E\, d^3\, k. \tag{3}$$

In particular, the values

$$f(^{12}C) = 0.9, \quad f(^{56}Fe) = 0.82, \quad f(^{197}Au) = 0.78, \tag{4}$$

were used in [7, 8] for extracting the nuclear transparency from the data.

It was recently pointed out in [6] that interpreting transparency measurements at high energies performed in the transverse kinematics, with the cuts on the momentum of the struck nucleon and the energy of the produced system, requires a re-evaluation of the quenching which was observed in the low energy domain. In particular, if one would use the same quenching for excitation of $s-, p-$ hole states in the carbon as the one observed at the low $Q^2 \leq 0.3\,GeV^2$ (eq.1), the transparency $\mathbf{T}$ for the $^{12}C(e, e'p)$ s- and p-valence state

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region is about 0.8 for $Q^2 = 1\,GeV^2$. This number is much higher than the predictions of Glauber theory which should be a reasonable approximation for $Q^2 \geq 1\,GeV^2$ and should be a very good approximation for $E_N \geq 1$ GeV, corresponding to $Q^2 \geq 2\,GeV^2$. At the same time we demonstrated that the carbon data at $Q^2 = 1\,GeV^2$ for the differential $(e, e'p)$ cross section appeared to be consistent with the Glauber calculation provided one assumes a strong reduction of the quenching effect at large Q^2. In particular we used the NE-18 differential (e,e'p) cross sections for carbon to determine the quenching factor for $Q^2 = 1\,GeV^2$ to be ~ 0.9.

We further argued that a Q^2 dependence of quenching should be a natural phenomenon reflecting transition from low Q^2 interactions where photon interacts with quasiparticles to the interaction with nucleons at larger $Q^2 \geq 1\,GeV^2$. However, we see no reasons for a noticeable A-dependence of the correlation correction at high Q^2 and $A \geq 12$. Indeed the main source of the A dependence at high Q^2 would be the A-dependence of the short-range correlation contribution. According to the the analysis of high Q^2, $x > 1$ data(see e.g. [15]) the effect of the short range correlations changes by $\leq 20\%$ between A=12 and A=208. However, as we show below,this contribution itself in the considered integral is just a few %($\sim (5 \div 7)\%$ for carbon).

In this paper we extend the analysis of [6] in several directions. We analyze the transparency measured recently in [8] for a range of nuclei, focusing at $Q^2 = 1.8\,GeV^2$ for which both integrated cross sections and differential cross sections are available. Our choice of Q^2 is motivated by a very good understanding of NN interactions for the corresponding energy of the ejected nucleon $E_p \approx 1 GeV$ - the Glauber theory is known to describe numerous data on elastic and quasielastic pA interactions at this energy with a typical accuracy of few percents, see review in [16]. Also, due to a weak energy dependence of σ_{pN} between $E_p \approx 1\,GeV$ and $E_p \approx 2\,GeV$, and the smallness of the color transparency effects for the $Q^2 \leq 4\,GeV^2$ range, one expects a very weak dependence of transparency on Q^2 for $2\,GeV^2 \leq Q^2 \leq 4\,GeV^2$. This is certainly consistent with the data. Hence adding higher Q^2 data would not add much to the main thrust of our analysis. We observe that measurements of $\mathbf{T}$ in the transverse kinematics of $x = 1$ are not sensitive to the high momentum component of the nuclear wave function since the cross section is proportional to $\int \frac{S(\mathbf{k},E)}{k} d^3k dE$ rather than to $\int S(\mathbf{k}, E) d^3k dE$. Further reduction in the uncertainties is reached by using information on the cross sections of (e, e') scattering at $x = 1$ and $Q^2 \sim 1\,GeV^2$ measured at Jlab [17] which allows to determine independently $\int \frac{S(\mathbf{k},E)}{k} d^3k dE$ with an accuracy of few %. Using this information we calculated the transparency for the kinematics of the E91-013 experiment for carbon, iron and gold and find that with an appropriate normalization of the impulse approximation cross section we obtain a very good description of the data.

We also check our conclusions about the noted reduction of quenching by comparing the results of our calculations with the $(e, e'p)$ data from the Jlab experiment [18] for the differential cross sections. We will show that excellent agreement is observed, without any adjusted parameters, for the region $k_N \leq 200\,MeV/c$, where contribution of the short-range

correlations is small. This provides a very strong new evidence for the practical disappearance of the quenching at large Q^2.

In the end of the paper we consider implications for optimizing searches for color transparency in high Q^2 $A(e, e'p)$ processes. Numerical predictions for kinematics where the onset of the color transparency is expected will be presented elsewhere.

2 Definition of transparency - how large is the impulse approximation

Current experiments which study nuclear transparency perform measurements in a restricted region of recoil nuclear momenta and excitation energies. Hence to convert the measured cross section to the value of transparency $\mathbf{T}$ it is necessary to consider the ratio:

$$\mathbf{T} = \frac{1}{\sigma_{pwia}} \int_{\Delta^3 k} d^3\,k \int_{\Delta E} d\,E\,d\,\sigma_{exp}(\mathbf{k}, E) \equiv \frac{\int_{\Delta^3 k} d^3\,k \int_{\Delta E} d\,E\,S^{exp}(\mathbf{k}, E)}{\int_{\Delta^3 k} d^3 k \int_{\Delta E} d\,E\,S(\mathbf{k}, E)}. \tag{5}$$

The quantities $\Delta^3 k$ and ΔE in (5) define the ranges in missing momentum $\mathbf{k} = \mathbf{q} - \mathbf{p}$ and missing energy $E = \nu - T_p$. The value of transparency $\mathbf{T}$ is known to depend appreciably on the excitation energy, the missing momentum and angle between $\mathbf{k}$ and $\mathbf{q}$[19, 12].

In the kinematics of the NE18 and E91-013 experiments $|k|$ and ΔE were restricted by 300 MeV/c and 80 MeV. Besides, the transverse kinematics of the experiments corresponded approximately to $k_3 = 0$. Account for the kinematics of the quasielastic process leads to the following relationship between k_3 and the Bjorken scaling variable $x = \frac{Q^2}{2m_N \nu}$ valid at sufficiently large Q^2

$$\frac{k_3}{m_N} = \frac{1 - x + (M_A - M^*_{A-1} - m_N)/m_N}{\sqrt{(1 + 4m_N^2/Q^2)}}. \tag{6}$$

Thus, the $k_3 \approx 0$ condition implies in the kinematics of the NE18 and E91-013 experiments $x \approx 1$, and that the main contribution to the cross section is given by the region

$$\left(\frac{\vec{k} \cdot \vec{q}}{|\vec{q}|}\right)^2 \ll k^2. \tag{7}$$

Obviously, if no restrictions other than $k_3 \approx 0$ were imposed we would obtain the quasielastic contribution to the total cross section of the (e, e') cross section at $x \approx 1$ for the same Q^2. At sufficiently high Q^2 this cross section is proportional to

$$S(k_3 = 0) \equiv \int S(\mathbf{k_t}, k_3 = 0, E)d^2 k_t dE$$

which coincides with the integrated spectral function $F(y)$ in the y-scaling models for $y = 0$. An important feature of this integral is that it has a much smaller contribution from the high momentum component of the spectral function than the normalization integral $\int S(\mathbf{k}, E) d^3 k \, dE$ since

$$S(k_3 = 0) = \frac{1}{2} \int S(\mathbf{k}, E) \frac{d^3 k}{k} dE, \tag{8}$$

leading to a strong enhancement of the small k region. This, in turn, implies that for a given kinematics the contribution of the large excitation energies ($\Delta E \geq 80 - 100 MeV$), which is predominantly due to the short range correlations, is also insignificant. Therefore, we can use mean field models to calculate the value of $F(y = 0)$ as measured in the (e, e') processes for $Q^2 \sim 1 \, GeV^2$ where inelastic contributions are still very small. Note that the account of the inelastic contributions allows for a good description of the Q^2 dependence of the ratio $\sigma_{eA}(x, Q^2)/\sigma_{eD}(x, Q^2)$ at $x = 1$, over a wide range of Q^2 [15]. In our calculations we used the Hartree-Fock-Skyrme model, which describes well many global properties of nuclei e.g. the energy binding, the spectra of the single particle states, root mean square radii and the shape of the proton and neutron matter distributions [20]. In this model, the spectral function is given by

$$S_{HF}(\mathbf{k}, E) = \sum_\alpha n_\alpha \delta(E - E_\alpha) |\varphi_\alpha(\mathbf{k})|^2. \tag{9}$$

The occupation probabilities for the filled nuclear levels are $n_\alpha = 1$. The integral which determines cross section of the quasielastic scattering at $x \approx 1$ and $y = 0$ is

$$S_{HF}(k_3 = 0) = 2\pi \int_0^\infty \sum_\alpha n_\alpha |\varphi_\alpha(k)|^2 \, k \, d \, k. \tag{10}$$

The results of the calculation are presented as the solid curve in Fig. 1. They are compared to the values of $F(y = 0)$ extracted from the inclusive (e, e') data of [17] in the vicinity of $x = 1$ at $y = 0$. These experimental values were corrected for a small contribution of inelastic processes using the analysis of [15], which described well the onset of the dominance of the inelastic contribution with increase of Q^2. The correction is about 3% (6%) for $Q^2 = 1.0(2.0) \, GeV^2$. One can see that the data are described very well without any adjusted parameters. Note that the IPSM spectral function which was used in the experimental analysis of NE18 and E91-013 [21] reproduces reasonably (dot-dashed line in Fig. 1) the weak A-dependence of the data though it somewhat overestimates the absolute value of the integral (10). At the same time an additional renormalization factor $f(A)$, Eq.(3), introduced in [7, 8, 18], does a good job for $A = 12$ but leads to much stronger A-dependence of the integral(dashed line in Fig. 1) than suggested by our calculations and by the data. We have also checked that the estimate of the integral (10) with the phenomenological models of the spectral functions, like, for example, those of [22], which includes the 15% contribution of the short-range correlations from region $k \geq 300 \, MeV/c$ in the normalization integral for the spectral function, coincides with our results for (10) within 5%. Also, in this model only 5%
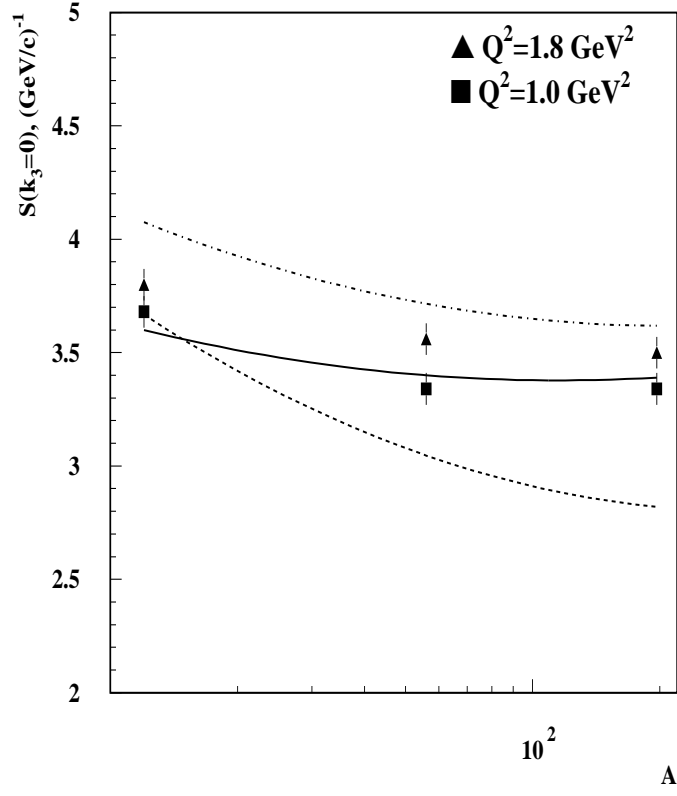
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Figure 1: Comparison of the scaling function $F_{A(e,e')X}(y = 0, Q^2)$ extracted from the data[17] and corrected for the inelastic contribution with the values of the integral (10) $S(k_3 = 0)$ calculated in the Hartree-Fock-Skyrme model(solid line) and in the shell model used in [7, 8, 18](dash-dotted line). The value of the integral (10) used in [7, 8, 18] in the denominator of Eq.(5) for extracting the nuclear transparency from the data is shown by the dashed line.

of the integral originates from the region of $k \geq 300 MeV/c$. This confirms our conclusion about the strong suppression of the short range correlation contribution in the transverse kinematics of [7, 8, 18] due to the specific properties of the integral (10). It is worth noting that already this comparison gives a new confirmation of our result for the value of the quenching factor $\eta \approx 0.9$, extracted in Ref. [6] from the comparison of the calculated momentum distribution in the C(e,e'p) process to that measured in the NE18 experiment at $Q^2 = 1\,GeV^2$.

Hence we conclude that the wave functions we use are sufficiently realistic to estimate the integral quantity entering the denominator of (5) in the calculation of the transparency in the $A(e, e'p)$ reactions.

3 Exclusive $(e, e'p)$ cross section

A more stringent test of the wave functions and interpretation of the data can be reached using differential data from E91-013 [18]. The differential cross section of the $(e, e'p)$ were calculated using the Hartree-Fock-Skyrme wave functions and the Glauber type model of the FSI for $(e, e'p)$ reactions[12, 13] [1]. The cross section can be represented in the same form as the impulse approximation with a substitution of the spectral function by the sum of the distorted shell momentum distributions given by

$$S_{HF}^{fsi}(\mathbf{k}) = \sum_{\alpha} n_{\alpha} \left| \int d\,\mathbf{r}\, e^{[i\mathbf{k}\cdot\mathbf{r}]}\, \phi_{\alpha}(\mathbf{r}) \left\langle (A-1) \right| \prod_{j=1}^{A-1} [1 - \Gamma(\mathbf{b} - \mathbf{b_j})\theta(z - z_j)] \left| (A-1) \right\rangle \right|^2. \quad (11)$$

Here

$$\Gamma(\mathbf{b} - \mathbf{b_j}) = (2\pi i p)^{-1} \int d^2 q_t\, exp[-\mathbf{q_t} \cdot (\mathbf{b} - \mathbf{b_j})] \cdot f_{NN}(\mathbf{q_t}),$$

and the NN amplitude for high energy protons is given by the expression

$$f_{NN}(\mathbf{q_t}) = \frac{p\sigma_{pN}^{tot}(1 - i\kappa_{NN})}{4\pi} e^{-\frac{B^2 q_t^2}{2}}.$$

The values of the total proton-nucleon cross section σ_{pN}^{tot}, the slope parameter B and the real-to-imaginary ratio κ_{pN} of the pN amplitude are well known[16] for the 970 MeV protons corresponding to the $(e, e'p)$ reaction at $Q^2 = 1.82\,GeV^2$. Results of our calculation for the distorted momentum distributions using eq.11 and the HF spectral function are compared to the data of [18] in Figs. 2, 3, 4. Taking into account that our calculations do not comprise any free parameters, one observes a fair agreement with experimental data, at least for momenta of the bound proton ≤ 200 MeV/c. A discrepancy at momenta above 200 MeV/c, which increases with A, can be considered as an evidence for the elastic incoherent rescattering processes for the outgoing nucleon (this effect will be considered elsewhere).

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[1]Note that we neglect in this calculation corrections due to effects of the short-range correlations in the propagation of the knocked out nucleon through the nucleus, which are known to be a small $\leq few\%$ correction for small struck nucleon momenta[23, 24].
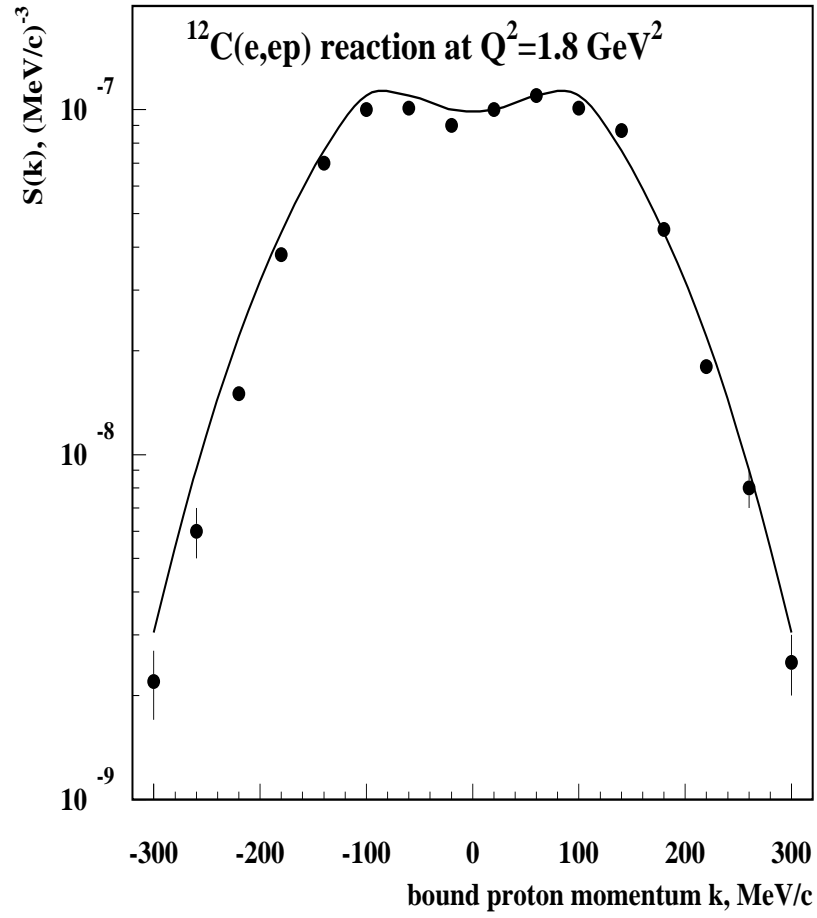
Figure 2: Comparison of the calculated momentum distributions for $^{12}C(e, e'p)$ at $Q^2 = 1.8\,GeV^2$ with E91-013 [18] data.

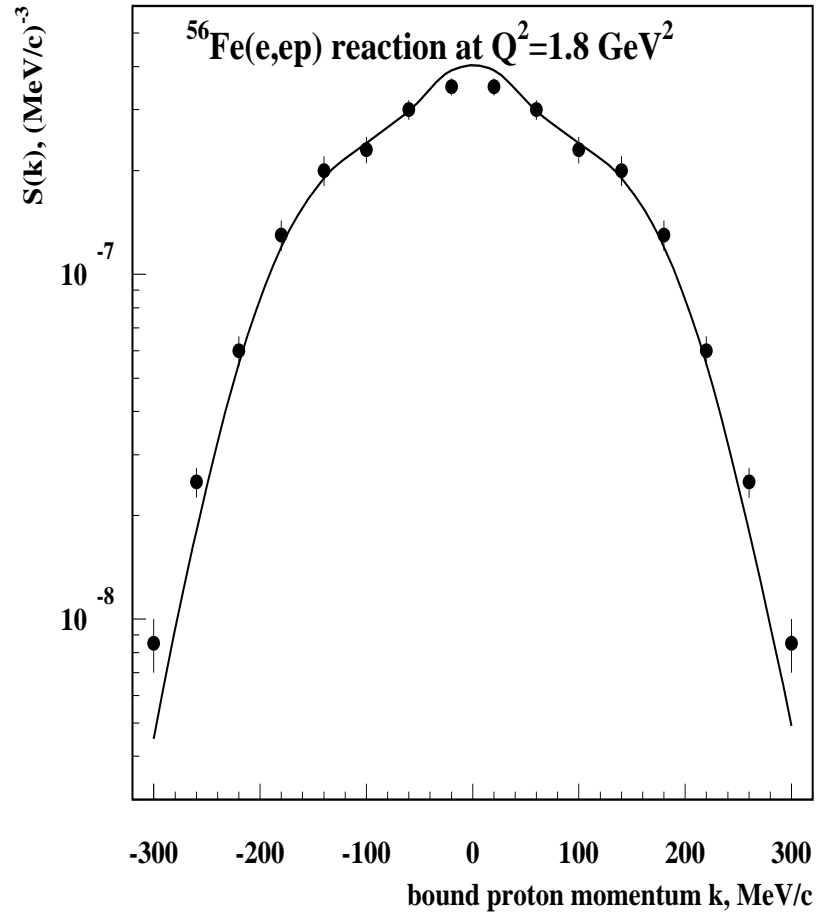Figure 3: Comparison of the calculated momentum distributions for $^{56}Fe(e, e'p)$ at $Q^2 = 1.8\,GeV^2$ with E91-013 [18] data.
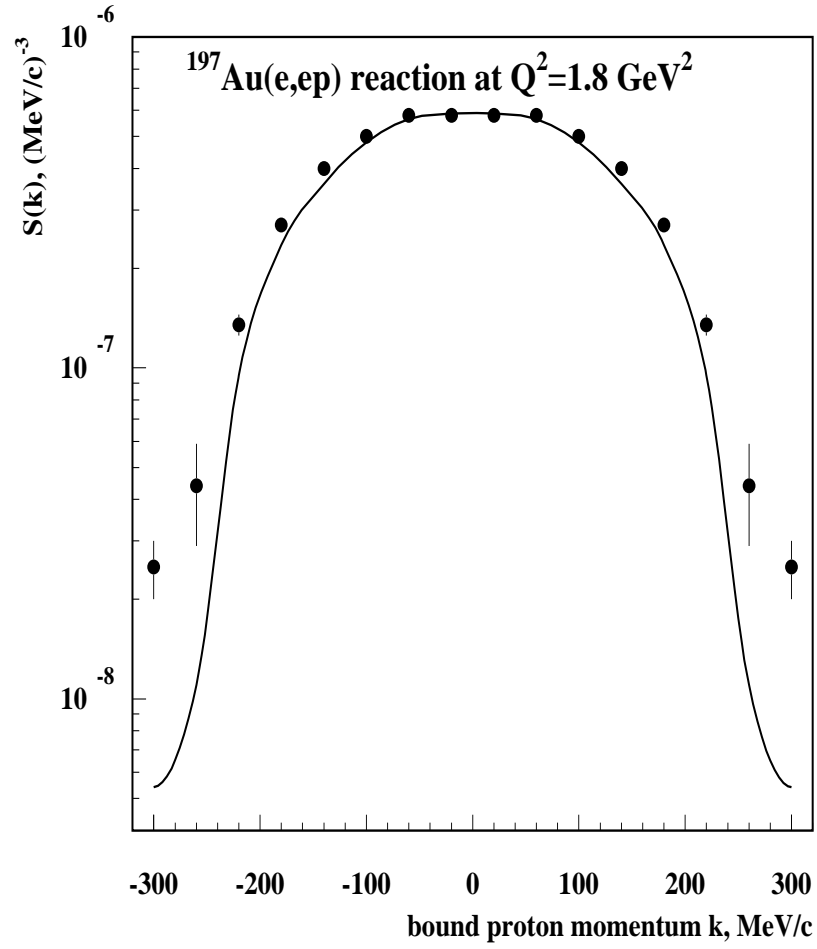
Figure 4: Comparison of the calculated momentum distributions for $^{197}Au(e,e'p)$ at $Q^2 = 1.8\,GeV^2$ with E91-013 [18] data.
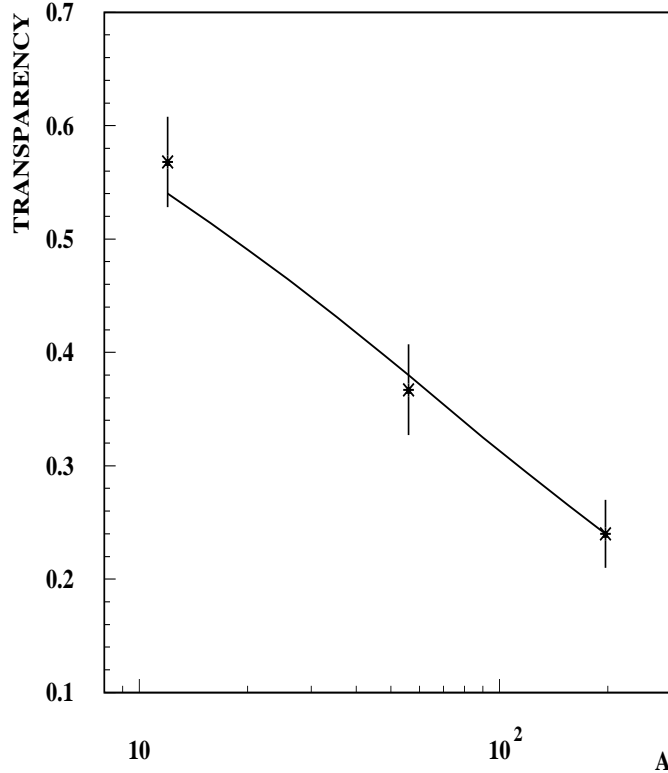
Figure 5: Comparison of the transparency calculated in the Glauber model for the FSI (solid line) with the measured nuclear transparency[8] corrected for the difference in the impulse approximation cross section.

4 Inclusive transparency in $A(e, e'p)$ reaction.

The E91-013 experiment at Jlab[8] which we discussed in the previous section also reported new values for the nuclear transparency which are consistent with the NE18 data but has somewhat better accuracy. In the previous sections we have demonstrated that both the numerator and the denominator in the definition of the transparency in Eq.(5) in the kinematics of the NE18 and E91-013 are sensitive to assumptions about the spectral function, but are strongly constrained by the (e, e') and $(e, e'p)$ data at $x \sim 1$ and $Q^2 \sim (1 \div 2) \, GeV^2$. This allows us to treat **T** with much smaller uncertainties than before and use it to obtain a suplementary evidence of the single particle strength restoration at high momentum transfer.

We obtain theoretical value of **T** from Eq. 5 by using the spectral functions $S_H F(k_3 = 0)$ (Eq. 10) and by integrating Eq.(11) to account for the FSI in the kinematics of [18]. The result

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of calculation is presented by solid curve in Fig.5. To compare these results with the data in a way consistent with our finding in section 2 we need to use the impulse approximation cross section consistent with the results presented in Fig. 1 and with the theoretical calculation of **T**. The simplest procedure is to correct the transparency values presented in [7, 8, 18] using in the denominator of Eq.(5) the value of the cross section in the impulse approximation given by our spectral function which differ from the value used in [7, 8, 18] by the factor $S_{IPSM}(k_3 = 0)f(A)/S_{HF}(k_3 = 0)$ (the factors are 1.02 for carbon, 0.896 for iron and 0.83 for gold). This leads to the corrected experimental values of the transparency shown in Fig.5 which are in a good agreement with results of calculations. We want to emphasize that this modification of the values of **T**, presented in [7, 8, 18], arises solely due to the change of the theoretical estimate of the impulse approximation cross section used in [7, 8, 18] to ensure consistency with results of the (e,e') measurements.

5   The Q^2 dependence of quenching

At first glance, the comparison with the data performed in previous Sections leaves no room for the presence of single particle strength quenching at $Q^2 \geq 2 GeV^2$. However to make the final conclusion one should carefully take into account experimental errors and uncertainties of the calculations. Generally, the accuracy of the Glauber approach in the description of the proton-nucleus interaction in high energy kinematics of the (e,e'p) reaction at $Q^2 \geq 2\,GeV^2$ is estimated to be small (a few %) as long as no new physics like color transparency is present. There exists also a few % uncertainty due to the use in the calculation of a definite set of the Hartree-Fock wave functions and neglecting effects of the short-range correlations in the calculation of the normalization integral (10). Hence, a possibility of the quenching of order $\approx 10\%$ cannot be excluded. However, this is definitely much smaller than $\eta(^{12}C) = .57 \pm .02$ determined from the low Q^2 data [6].

It should be noted that the analysis of (e,e'p) data is more definitive at high energy and high momentum transfer than in the low energy kinematics. The kinematical off-shell effect in the ep vertex due to the Fermi motion of nucleon, studied e.g. by De Forest[14], is minimized in the high energy limit. Also, the renormalization of the ep vertex due to the inability of a low Q^2 photon to resolve the short-range and long-range correlations of interacting proton with the rest of the nucleons is evidently more essential in the low Q^2 kinematics. Within the quasiparticle approach, such a renormalization can be performed by using the form factor of a quasiparticle which is softer than for a free nucleon, because at low resolution a low momentum bound nucleon in the nuclear medium is dressed by a cloud of virtual nuclear excitations. With increase of the momentum transfer above the Fermi-momentum of the bound nucleon, $k_F \approx (220 \div 260)\,MeV/c$, this renormalization of the electron-proton vertex disappears, and we deal with the form factor of a free nucleon.

Besides, taking into account the FSI at low energies is more cumbersome because one needs to deal with the optical potentials which are determined from fits to the proton-nucleus

elastic scattering data. Such a treatment ignores the difference in the space geometry of proton-nucleus elastic scattering, dominated by the interaction with the nuclear surface, and the proton propagation from the nucleus interior in the electron induced nucleon knockout reaction.

To summarize, we have demonstrated, based on the joint analysis of the exclusive A(e,e'p) and A(e,e')X data at $Q^2 \geq 1\, GeV^2$, that the actual quenching factor which enters into cross sections of the exclusive quasielastic processes differs from the one used in [7, 8, 18] and is practically insensitive to the probability of the short-range nucleon correlations in nuclei. We found further evidence for the dependence of the single particle strength quenching in the exclusive (e,e'p) reactions on the momentum transfer. The strong effect (about 40 %), observed in the low energy phenomena, practically disappears with increase of Q^2, when a probe resolves the quasiparticle structure of the nucleon due to the long-range correlations inside the nuclear medium. In the discussed transverse kinematics only a very modest quenching (less than 10%) may survive in the exclusive (e,e'p) reaction at high Q^2 and $|k| \leq 300 MeV/c$.

A strong Q^2 dependence of quenching comes very naturally in the Fermi liquid theory [25, 4, 26] and really represents the generic property of fermionic systems where the interaction between fermions is described by a renormalizable theory[27], like QED or QCD, since in this case the wave functions of constituents depend strongly on the resolution scale.

A high precision measurements of A(e,e') scattering and the differential cross sections of the exclusive A(e,e'p) reactions at Q^2 in the range $(1 \div 2)\, GeV^2$ would be very useful for an accurate estimate of the quenching effect, and to determine the experimental values of nuclear transparency. The kinematics $\Delta E \leq 80 MeV, |k| \leq 300 MeV/c$ appear to be optimal for searches of color transparency at moderate and high momentum transfers in the $(e, e'p)$ reactions, in order to understand the phenomenon of expanding of small size quark configurations in hard processes.

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